

Extraction of the Ratio of the $N^*(1535)$ Electromagnetic Helicity Amplitudes from Eta Photoproduction off Neutrons and Protons

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Using the recent precise measurements of eta photoproduction in proton and deuteron targets, we extract the ratio of the helicity amplitudes $A_{1/2}^n/A_{1/2}^p$, for the excitation of $N^*(1535)$, in the effective Lagrangian approach. It is fairly model-independent, free from the final-state interaction effects, and negative as predicted by the quark models. We stress the importance of polarization observables in further elucidation of the $N^*(1520)$ photoexcitation amplitudes.

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The study of eta photoproduction near threshold off nucleons has been established as a precision tool to study electrostrong properties of the $N^*(1535)$ resonance predominantly excited in this process [1,2]. This should allow us to test an important prediction of the quark model [3], a lack of flavor symmetry in the amplitudes for exciting $N^*(1535)$ off proton and neutron targets by electromagnetic probes. Thus, the calculated ratio of the transverse helicity amplitudes in the two targets is [3]:

$$A_{1/2}^n = cA_{1/2}^p, \quad (1)$$

where the coefficient c is predicted [3] to be negative, with its magnitude varying from about 0.7 to unity. Considerable relativistic corrections are indicated [3] in estimating these amplitudes, but there is no theoretical dispute about the sign of c . This flavor asymmetry of Eq.(1) has also important implications in photo- and electroproduction of eta mesons in complex nuclei.

Main purpose of this Letter is to test the inequality in the magnitudes of the above helicity amplitudes in the proton and neutron targets, by appealing to the new, precise data of near-threshold photoproduction of etas from the proton and deuteron targets at Mainz [2,4]. We use the proton data [2] to fix unknown parameters of the strong sector of our tree-level effective Lagrangian [1], and utilize the extracted neutron cross-sections [4] to determine the unknown $A_{1/2}$ helicity amplitude to excite the $N^*(1535)$ state, fixing the $N^*(1520)$ electromagnetic helicity amplitudes by the proton data and the quark model. A comparison of this amplitude with that for proton would then yield the test of the flavor dependence of the helicity amplitudes, predicted by the quark model. We then retain all strong interaction parameters and fit the rest of the parameters in our effective Lagrangian approach (ELA) to the neutron data. Finally, we investigate the importance of polarization observables in further sorting out of the $N^*(1520)$ photoexcitation amplitudes.

An inference of neutron cross-sections from the deuteron data [4] is far from being straightforward. The loosely bound neutron in deuteron *is* the most convenient target for eta photoproduction for this purpose [4], *but nuclear corrections must be made* to extract

neutron cross-sections from those of deuteron [5]. Krusche *et al.* [4] have obtained the best agreement between their proton [2] and deuteron [4] data by constraining the ratio of the neutron to proton cross-sections as

$$\sigma_n^{exp}/\sigma_p^{exp} = 0.66 \pm 0.07, \quad (2)$$

for lab photon energies from eta production threshold up to 792 MeV. This holds reasonably well both for the differential and the total cross-section. We shall use this *experimentally inferred number* as a constraint for our effective Lagrangian approach.

Our analysis reported here is different from that of Krusche *et al.* [4]. We take into account the possible model-dependence in the contributions other than that for $N^*(1535)$. We extract the ratio of helicity amplitudes for $N^*(1535)$ for proton and neutron targets and show that this extraction can be done in a model-independent fashion.

At the first sight, one might conclude that the experimental result (2) straightforwardly implies (1), but this is not necessarily so. Only in the naive approximation that the excitation of $N^*(1535)$ is the *sole* contribution to the eta photoproduction, one can readily infer this connection. This is because the non-resonant nucleon and vector meson exchange contributions [1] play important but significantly different roles in proton and neutron targets, as do the excitations of other resonances such as $N^*(1520)$ [1]. Investigations of these contributions to the photoproduction of eta mesons off neutrons constitute an important part of this work. Here we would defer from other recent theoretical treatments of the process [5,6]. Many of these works also stress the unified treatment of pion and eta channels. While this is theoretically desirable, current uncertainties [7] of the strong interaction (π , η) data base do not allow us to carry out such an ambitious treatment satisfactorily at present. Thus, we shall not utilize the latter here.

We shall now discuss the theoretical ingredients of our ELA to describe the photoproduction of eta off neutrons,

$$\gamma + n \rightarrow n + \eta, \quad (3)$$

near threshold. This discussion parallels our ELA treatment [1] of the process off protons, $\gamma + p \rightarrow p + \eta$. Thus, at the tree-level, we can write the invariant matrix element $i\mathcal{M}_{fi}$ in the standard form [1]

$$i\mathcal{M}_{fi} = \bar{u}_f(p_f) \sum_{j=1}^4 A_j(s, t, u) M_j u_i(p_i), \quad (4)$$

with $M_1 = -1/2\gamma_5\gamma_\mu\gamma_\nu F^{\mu\nu}$, $M_2 = 2\gamma_5 P_\mu(q_\nu - k_\nu/2)F^{\mu\nu}$, $M_3 = -\gamma_5\gamma_\mu q_\nu F^{\mu\nu}$, $M_4 = -2\gamma_5\gamma_\mu P_\nu F^{\mu\nu} - 2MM_1$, where p_i, p_f are the nucleon four-momenta, k and q are the photon and the meson four-momenta, $P^\mu = (p_i + p_f)^\mu/2$, $F^{\mu\nu}$ is the electromagnetic field tensor. The *neutron* Born terms will give, for the meson- nucleon pseudoscalar interaction [8],

$$A_1^{ps} = A_2^{ps} = 0, \quad (5)$$

$$A_3^{ps} = -eg_\eta \frac{k_n}{2M} \left[\frac{1}{s - M^2} - \frac{1}{u - M^2} \right], \quad (6)$$

$$A_4^{ps} = -eg_\eta \frac{k_n}{2M} \left[\frac{1}{s - M^2} + \frac{1}{u - M^2} \right], \quad (7)$$

with $k_n \simeq -1.91nm$, g_η , the pseudoscalar ηNN coupling strength, M , the nucleon mass. The above results follow from the corresponding proton contributions, by using isospin symmetry and noting the trivial differences between neutron and proton in charge and anomalous magnetic moment. The corresponding results for the pseudovector interaction is [8]

$$A_1^{pv} = eg_\eta \frac{k_n}{2M^2}, A_k^{pv} = A_k^{ps}, k = 2, 3, 4. \quad (8)$$

Here we utilize the pseudoscalar eta-nucleon coupling.

The t-channel vector meson exchange contributions for the neutron eta photoproduction can be likewise obtained from the proton case by the isospin symmetry. Given the fact that there is only isovector contribution for the ρ case, but not for the ω -exchange, the A coefficients for the ρ exchange amplitude has to be multiplied by -1 , relative to the proton:

$$A_i^\rho(n) = -A_i^\rho(p), \quad (9)$$

$$A_i^\omega(n) = A_i^\omega(p). \quad (10)$$

For the resonance exchanges, the isospin symmetry of the effective Lagrangian also allows us to construct the neutron amplitudes from those of the proton [1]. Thus, the proton coupling strengths in terms of transition amplitudes are $k_R^p = k_R^s + k_R^v$, while those for the neutrons are:

$$k_R^n = k_R^s - k_R^v, \quad (11)$$

where s and v represent the isoscalar and isovector resonance coupling strengths respectively. This completes the transcription of the proton couplings into the neutron ones. The complexity of the spin-3/2 resonance propagators [9] will be treated in the same way as in the proton case [1], with the parameters controlling the spin-1/2 sector unchanged from the proton case, except when we need to fit the neutron data. We stress the importance of this physics in our theoretical considerations.

The general treatment of the neutron photoproduction requires, for E_γ varying from the eta threshold ($E_\gamma^{n(th)} = 706.94 \text{ MeV}$) to 1200 MeV, the consideration of resonances $N^*(1440)$, $N^*(1535)$, $N^*(1520)$, $N^*(1650)$ and $N^*(1710)$. However, the Mainz *proton data* can be adequately treated in an ELA which contains only the nucleon Born terms, ρ , ω vector meson exchanges in the t-channel and the contributions of $N^*(1535)$ and $N^*(1520)$, as shown by our nice fit to the Mainz proton angular distribution data sampled in Fig.1, yielding g_η , the pseudoscalar eta-nucleon coupling constant, to be approximately 2.3. The contribution of $N^*(1535)$ *dominates*, but the roles of the other contributions are *essential* in order to reproduce the observed angular distributions [2]. We shall use this effective version of our ELA to *predict* the angular distributions for the eta photoproduction from the neutron target. For this we take the value of c in (1) to be equal to -0.83 , as suggested by recent quark model estimates, for example, by Capstick [3]. We also use the quark model as a guide to convert the proton $A_{1/2}$, $A_{3/2}$ helicity amplitudes for the $N^*(1520)$ excitation off neutrons.

We infer neutron data from deuteron observations [4] as follows:

$$\frac{(d\sigma/d\Omega)_n}{(d\sigma/d\Omega)_p} \simeq \frac{\sigma_n}{\sigma_p} \simeq \frac{2}{3}. \quad (12)$$

In Table I, we give the E_{0+} amplitudes for the proton and the neutron targets for photo-production of etas at threshold, obtained from typical fits to the proton [2] and our inferred neutron data. We also compare our estimates with those of Tiator *et al.* [6]. Various non-resonant and resonant contributions can now be compared for the two targets. The dominance of the $N^*(1535)$ excitation emerges in all fits. It is, however, a result of *different* model-dependent background contributions in the two targets.

We now display our predictions of typical angular distributions of the eta photoproductions off neutrons in Fig. 1, along with our fits of the Mainz proton data. The role of the resonances alone is also shown. The predicted angular distribution for neutron nicely matches the two-third ratio between neutron and proton, inferred experimentally by Krusche *et al.* [4] from their deuteron target experiment. This suggests that *the value of c equal to -0.83 is consistent with the results of the Mainz deuteron experiment.*

We can now turn the last argument around. By demanding a fit to the empirical observation (2) of Krusche *et al.* [4], we can extract a parameter ξ_n for $N^*(1535)$, defined [1] in the usual notation, similar to our extraction [1] of ξ_p ,

$$\xi_n = \sqrt{\chi_n \Gamma_\eta A_{1/2}^n} / \Gamma_T, \quad (13)$$

where the kinematic factor χ_n can be computed from the neutron mass and other kinematic parameters of the $N^*(1535)$ excitation. We can characterize the electrostrong property of $N^*(1535)$, as inferred from the neutron experiment, to be

$$\xi_n = (-1.86 \pm 0.20) \times 10^{-4} MeV^{-1}. \quad (14)$$

The error here includes an estimate of our ELA model uncertainties. From our analysis [1] of the proton data [2], we have

$$\xi_p = (2.20 \pm 0.15) \times 10^{-4} MeV^{-1}. \quad (15)$$

We can now combine our inferences from the Mainz proton and the deuteron experiments by taking the ratio of the extracted parameters ξ_n and ξ_p :

$$\frac{\xi_n}{\xi_p} = \sqrt{\frac{\chi_n}{\chi_p}} \frac{A_{1/2}^n}{A_{1/2}^p}. \quad (16)$$

In the above ratio, the strong interaction property of the $N^*(1535)$, arising from the decay of this resonance, drops out completely. Thus, from the recent Mainz experiments on eta photoproduction off proton and deuteron targets, we can extract, in a model-independent fashion, a ratio of the neutron to proton helicity amplitudes:

$$A_{1/2}^n/A_{1/2}^p = \sqrt{\frac{\chi_p}{\chi_n}} \frac{\xi_n}{\xi_p} = -0.84 \pm 0.15, \quad (17)$$

using $\chi_p/\chi_n \simeq 0.987$. This value compares very favorably with recent quark model estimates (e.g. that of Capstick [3], which yields about -0.83). The inference of this quantity, done here directly from the experiments in an essentially model-independent fashion, is the *central result* of this Letter. The sign of this quantity is negative, as predicted by the quark models [3].

In Fig.2, we show the differences between proton and neutron targets in studying polarization observables at the photon lab energy of 780 MeV, taking an example. We also demonstrate here the effect of changing the sign of the electromagnetic helicity amplitude $A_{1/2}$ for neutron to $N^*(1535)$ excitation. The consequence of the change of sign of this helicity amplitude for neutron is that polarization observables, viz., recoil nucleon polarization(RNP), polarized target asymmetry (PTA) and polarized photon asymmetry(PPA), *all change sign*, with the PPT showing maximum sensitivity. Thus, the theoretical prediction of the sign of this helicity amplitude for neutron, of crucial importance to nuclear excitation of the $N^*(1535)$ resonance, can be verified by the *sign of the measured polarizations*. The role of the D13 resonance, $N^*(1520)$, is demonstrated in Fig.3. It is correlated with the choice of the g_η . Polarization experiments for proton and neutron targets would thus be quite useful. For latter, the polarized ^3He target would serve as a polarized neutron target.

Fig.4 demonstrates the RNP as a function of the photon lab energy at cm angle 90° ,

compared with the data of Heusch *et al.* [11]. While the agreement with proton data is satisfactory, the quality of this data is not good. More experimental work is needed here.

In summary, we have extracted, using the effective Lagrangian approach [1] and the available new data of eta photoproduction from proton and deuteron targets [2,4], the ratio $A_{1/2}^n/A_{1/2}^p$, both in magnitude and in sign. In so doing, we have not made the simple assumption that only the contribution of $N^*(1535)$ be taken into account. The extracted ratio, of fundamental interest in nuclear physics, agrees nicely with the prediction of recent quark model estimates; it is now quite accurate to invite a precise estimate by lattice QCD methods. New polarization experiments, discussed in this Letter, can provide independent tests for this ratio and further theoretical insights into the nucleon resonance excitation. Our understanding of the eta photoproduction mechanism on proton and neutron, in turn, would help that in complex nuclei. The near cancellation of the sum of the proton and neutron helicity amplitudes to excite $N^*(1535)$ would have an important bearing in explaining the new Mainz experiment, which does not see any coherent contribution to the eta photoproduction in nuclei [10]. The resultant upper limit for the coherent cross-section, obtained from this experiment, supports our conclusion on the sign of the dominant helicity amplitude, for the $N^*(1535)$ excitation, for neutrons.

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Fig. 1: Angular distributions for eta photoproduction off protons for two sample values of E_γ , 716 and 775 MeV. Experimental points (circles) are from [2], and the dot-dashed line is our full effective Lagrangian fit, while dots represent resonances alone. Also shown are our predictions for the neutron target assuming $A_{1/2}^n/A_{1/2}^p = -0.83$ (solid line), vs. the inferred differential cross-section (stars). Here the long-dashed lines represent our predictions with resonances alone.

Fig. 2: The differential cross-section $d\sigma/d\Omega$, recoil nucleon polarization (RNP), polarized target asymmetry (PTA) and polarized photon asymmetry (PPA) for eta photoproduction off proton (dot-dashed line) and neutron targets (solid line). We also display (dashed line) the effect when $A_{1/2}$ changes sign for the neutron target from the negative value predicted by the quark model for the $N^*(1535)$ excitation. The photon lab energy, chosen here for illustrative purposes, is 780MeV .

Fig. 3: The comparison between the results of two different sets of $A_{1/2}$, $A_{3/2}$ for $N^*(1520)$. Solid line is the result of fitting our inferred neutron differential cross-sections from Krusche *et al.* [4] ($A_{1/2} = 43.8$, $A_{3/2} = 96.6$ for $N^*(1520)$). Dashed line is the result using the PDG amplitudes for $N^*(1520)$ ($A_{1/2} = -62$, $A_{3/2} = -137$). Observables are defined in Fig.2, $E_\gamma = 780\text{MeV}$. All amplitudes here are in the usual unit [1].

Fig. 4: Recoil nucleon polarization (dot-dashed line, proton; solid line, neutron) vs. E_γ , photon lab energy, at meson cm angle of 90° . Experimental points for proton are from Heusch *et al.* [11].

TABLE I. A comparison of various contributions to the E_{0+} multipole, in units of $10^{-3}/m_{\pi+}$, for the $\gamma + p \rightarrow \eta + p$ and the $\gamma + n \rightarrow \eta + n$ reactions, at their respective thresholds. The parameters, defined in [1], $\alpha = +1$ and $\Lambda^2 = 1.2\text{GeV}^2$ are used. The targets (Re/Im parts of the E_{0+} amplitude) are indicated. Our model parameters are fitted to the experiment of Krusche *et al.* [2] for protons, and our inferred data for neutrons [4]. A refers to the estimate by Tiator *et al.* [6], and B is the present work.

Contributions	Targets (Re/Im parts of the E_{0+} amplitude)							
	p (Re)	p (Re)	p (Im)	p (Im)	n (Re)	n (Re)	n (Im)	n (Im)
	A	B	A	B	A	B	A	B
Nucleon Born terms	-5.2	-3.4	0.0	0.0	3.6	2.3	0.0	0.0
$\rho + \omega$	3.0	2.9	0.0	0.0	-2.3	-2.0	0.0	0.0
$N^*(1535)$	12.9	12.2	6.0	8.5	-7.1	-10.5	-4.9	-7.3
$N^*(1520)$	--	1.6	--	0.0	--	-0.2	--	0.0
Total	10.7	13.3	6.0	8.5	-5.9	-10.4	-4.9	-7.3







